Equipment Scaling Calculations

The purpose of this document is to describe calculation methodology used to scale the Trojan Marinex Ballast Water Treatment Systems (BWTS).

The Trojan Marinex product suite consists of seven (7) models designed for treated rated capacity (TRC) of 150, 250, 500, 750, 1000, 1250, and 1500 m^3/h. The treatment system consists of filtration combined with UV disinfection. The system design is unique, in that the filter elements and the UV lamps are housed within a single treatment vessel.

1.0 SCALING FACTORS

Trojan is performing land-based testing with the Trojan Marinex Model 500, at a rated flow of 500 m^3/h. In accordance with section 2.3.13 of Annex 4 Resolution MEPC.174(58) Guidelines for Approval of Ballast Water Management Systems (G8) Section, land-based testing may be performed with downscaled equipment. Where the TRC is between 200 and 1000 m/h the test equipment may be downscaled to a maximum of 1:5 scale. For equipment with a TRC that is greater than 1000 m/h, the test equipment may be downscaled to a maximum of 1:1000 scale. In both cases, the tested unit shall not be smaller than 200 m^3/h.

The table below summarizes the models within the product suite, and their scale relative to the 500 m^3/h test unit. In all cases the scaling falls within the maximum allowed per G8.

Model	TRC (m^3/h)	Scale Relative to Test Unit	Maximum Allowable Scaling
150	150	1 : 0.3	1 : 5
250	250	1 : 0.5	1 : 5
500	500	Test unit	Test unit
750	750	1 : 1.5	1 : 5
1000	1000	1 : 2	1 : 5
1250	1250	1: 2.5	1 : 100
1500	1500	1 : 3	1 : 100

2.0 MATHEMATHICAL MODELLING AND/OR CALCULATION METHODS FOR SCALING

The modeling/calculation methods for scaling the filtration and UV portions of the Trojan Marinex systems are described in detail in the sections below.

2.1 Filtration

Trojan scaled the filtration portion of the treatment system based on maintaining a common filter loading rate (+/-<10%) between the tested model (500 m^3/h) and the other models in the product suite. The loading rate used for the scaling calculation is the highest operational loading rate (worst case, most challenging) which occurs during a filter backwash sequence. During a filter backwash sequence, up to three filter candles (depending upon model) are taken out of operation, thereby increasing the filter loading rate on the remaining elements.

The filter element design for each system remains identical in terms filter material, mesh size, filter candle length, candle diameter, candle sealing mechanism, and filter cleaning methodology. The number of filter candles per model will differ based on the rated flow rate. A summary of the models, number of filter elements, and flow per filter element (loading rate) is provided below.

Table 1 – Summary of Filter Loading Rates for the Trojan Marinex Product Suite

Model	TRC (m^3/h)	Total Number of Filter Elements	Number of Filter Elements in Operation During Backwash	Flow per Filter Element During Backwash (m^3/h)	Variance from Model 500 (tested system)
150	150	8	7	21.4	-6%
250	250	12	11	22.7	0%
500	500	24	22	22.7	0%
750	750	35	32	23.4	3%
1000	1000	48	45	22.2	-2%
1250	1250	55	52	24.0	6%
1500	1500	69	66	22.7	0%

2.2 UV Disinfection

Trojan has scaled the design of the UV Disinfection portion of the treatment unit based on maintaining an equivalent Reduction Equivalent Dose (RED) (+/- <10%) between the tested model (500 m^3/h) and the other models in the product suite.

Trojan calculates the RED delivered by each model, using a Computational Fluid Dynamics (CFD) model integrated with a UV light intensity model. This approach has been used by Trojan extensively in design of UV systems for disinfection of municipal drinking and waste waters for over ten (10) years. This approach is also described in the USEPA Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (UVGM) Appendix D.

The +/-10% criteria for assessing whether or not the RED is “equivalent” was selected based on the guidance provided in the UVGM. This value of +/- 10% is recommended by the UVGM for assessing the need for re-validation of UV based drinking water systems (UVGM Section 5.13).

The overall geometry of the UV portion of the BWMS remains the same for all models within the product suite. All models use the same lamps, lamp drivers, quartz sleeves, and sleeve cleaning mechanisms. The number of UV lamps per model will differ based on maintaining the equivalent RED as the TRC changes.

The following sections provide a detailed description of the CFD based methodology used to calculate the delivered RED and a summary of the RED calculations for the product suite.

2.2.1 Reduction Equivalent Dose Calculation Methodology

UV *Dose* can be calculated for any given micro-organism being treated as *Delivered Dose = UV Intensity x Exposure Time*. In order to model, or calculate, the UV dose, the factors influencing the intensity and time need to be considered. *UV intensity* in the system is a function of the mediums the emitted light must pass through (air, quartz sleeve, and water), while the *time* in any given system is a function of the flow field; which is dictated by the system geometry and flow rate. Trojan is able to calculate the UV Dose by utilizing a combination of commercially available Computational Fluid Dynamics (CFD) software to generate the flow field, and in-house software to determine the UV light field. What follows below is a synopsis of how the two software's are employed together to calculate the Delivered UV Dose for the Trojan Marinex product suite.

2.2.1.1 Flow Field – Computational Fluid Dynamics

In order to perform CFD, first the fluid volume, defined by the bounds (walls) of the system, must be discretized into many smaller volumes or meshed, and then conservation equations are solved for each mesh cell. Once the solution is generated, the results can be probed and the relevant properties ascertained.

Geometry Discretization / Meshing

When generating the mesh for each system being analyzed, the major internal features are captured (quartz sleeves, wipers, filter surfaces, support rods, baffles, etc.). The minor features, for example fastener heads, are omitted. As these small features are not expected to influence the flow field due to their small scale, removing them makes the meshing process easier (small features can be difficult to resolve accurately). Shown below in
Figure 1 is the model used for the 500 m3/h system, which includes all the main features influencing flow within the UV treatment zone.

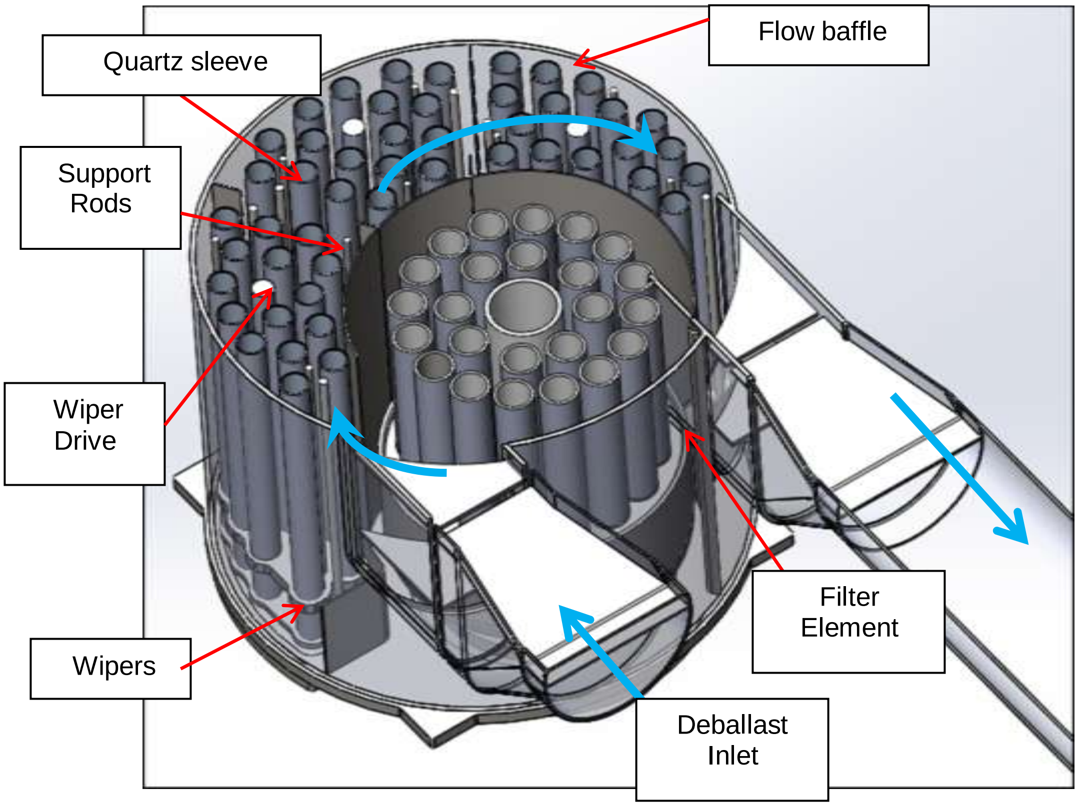

Figure 1 – Cut-away view of Marinex 500 internal geometry (turquoise arrows indicate flow direction).

As the fluid volume is discretized, built-in algorithms are used to refine critical areas within the UV treatment zone. The regions around the quartz sleeves are of particular importance. Typically when generating the mesh, a minimum element size is specified to determine the smallest feature that can be captured. For modeling the Marinex product suite the minimum mesh size specified was typically between 3 and 5 mm. This resulted in total element counts ranging from 3 to 6 million (depending on the model examined – small systems have a smaller total count conversely large system have a larger total count). Figure 2 below shows an example of the cross-sectional slice through the three-dimensional Cartesian mesh of the Marinex 500 treatment unit.

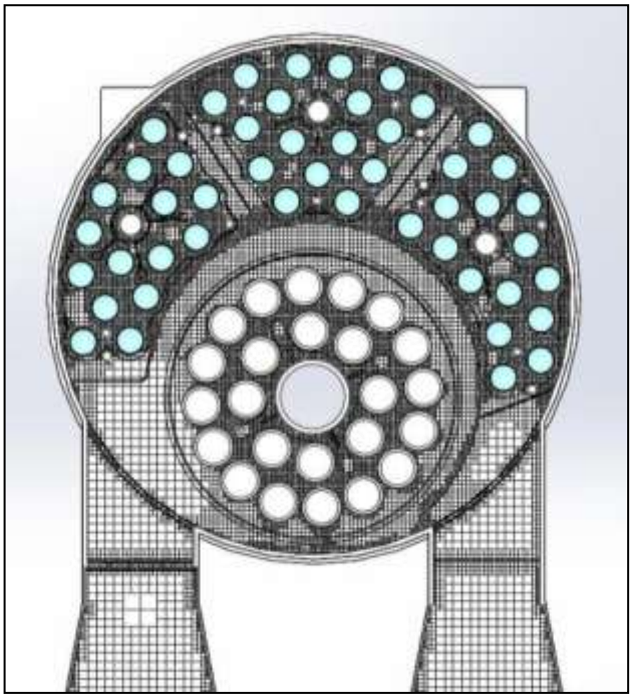

Figure 2 – Mesh example for Marinex 500 system - mid-section cross-sectional slice through 3D domain.

With geometries as intricate and complex as these treatment units, it is difficult to perform mesh sensitivity analyses. A standard approach of increasing element counts along principle axes and examining the effect on critical outputs would be extremely challenging if not impossible. With that said, a mesh independence analysis was performed when examining the 1250 m^3/h treatment unit. The system was analyzed with standard mesh settings and then again with a refined mesh with a nearly 50% larger total element count the results of which are found in the table below. It was found that the refined mesh showed nearly equivalent results as the standard mesh. Subsequently the standard settings applied in the analyses of the treatments units are considered sufficient.

Mesh Sensitivity	**Element Count**	**RED [mJ/cm^2]**	**Head Loss [m]**
Standard Mesh	6,556,681	57.6	0.740
Refined Mesh	9,737,057	57.4	0.721
Percent Difference	49%	0.4%	2.6%

Solver

CFD is based on the simple concept of solving conservation of mass and momentum equations for every mesh element; equations 1 and 2 below respectively. These transport equations are discretized and solved iteratively until equation residuals are significantly small enough such that the equation can be considered solved.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]+\frac{\partial}{\partial x_j}(-\rho\overline{u'_i u'_j}) \qquad (2)$$

The three-dimensional flow field (pressure, velocity and turbulence) is solved within the domain of each treatment unit using the Flow Simulation add-on in the commercially available software Solid Works Premium 2012 x64 2012 SP4.0. The closure model used to capture turbulence during the simulations was the standard k-ε model. The flow rate is defined by the system TRC (eg. Model 500 has a TRC of 500 m^3/h). For the disinfection analysis, particle tracks were generated from the flow simulations. The number of particles tracked for each configuration was between 3,000 and 5,000 depending on the model, released at a plane leading into the UV treatment zone. Particles were defined with the same density as the fluid to remain neutrally buoyant and with diameters of 0.0001m; these properties allow the particles to mimic the microbes found in the influent.

Discrete Phase Model / Particle Trajectories

To calculate the dose delivered to the organisms in the system, each organism should be tracked in the flow field. Therefore in addition to solving transport equations for the continuous phase, a discrete second phase is simulated in a Lagrangian frame of reference. This second phase consists of spherical particles (which represent the organisms) dispersed in the continuous phase. The CFD software computes the trajectories of these discrete phase entities. The coupling between the phases and its impact on both the discrete phase trajectories and the continuous phase flow can be included. The discrete phase modeling includes the discrete phase inertia, hydrodynamic drag, and the force of gravity as well as the effects of turbulence on the dispersion of particles due to turbulent eddy's present in the continuous phase.

Shown below in 3 and Figure 4 are particle tracks colored by velocity from the three-dimensional simulations of the 500 m^3/h and 1250 m^3/h treatment systems respectively. It can be seen that the flow field through the UV treatment zone of the systems is quite complex.

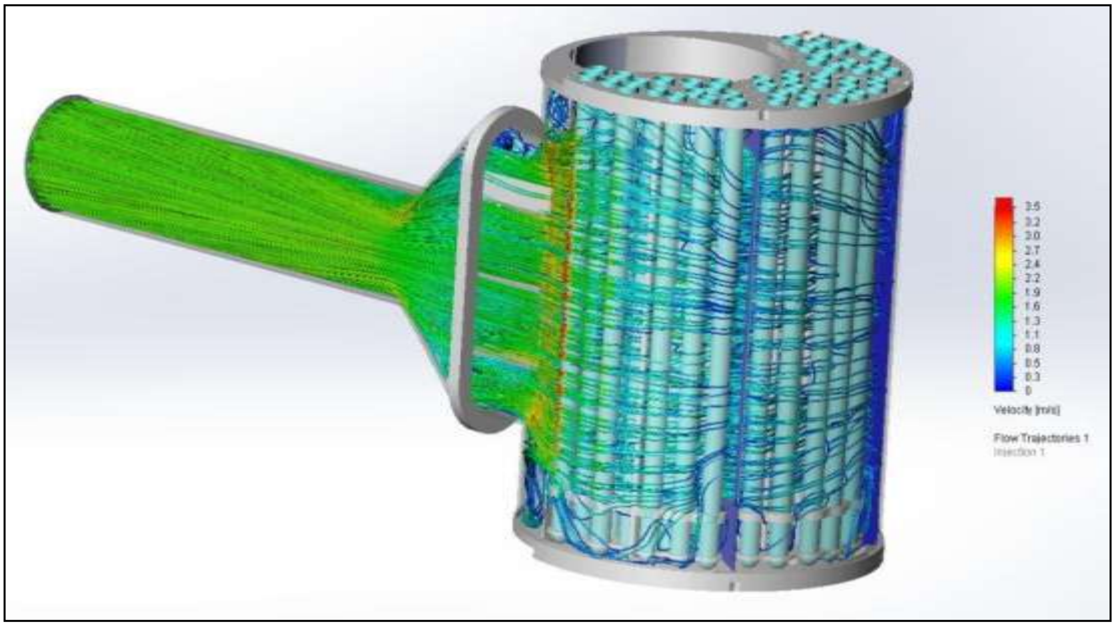

Figure 3 – Particle tracks colored by velocity through the Marinex 500

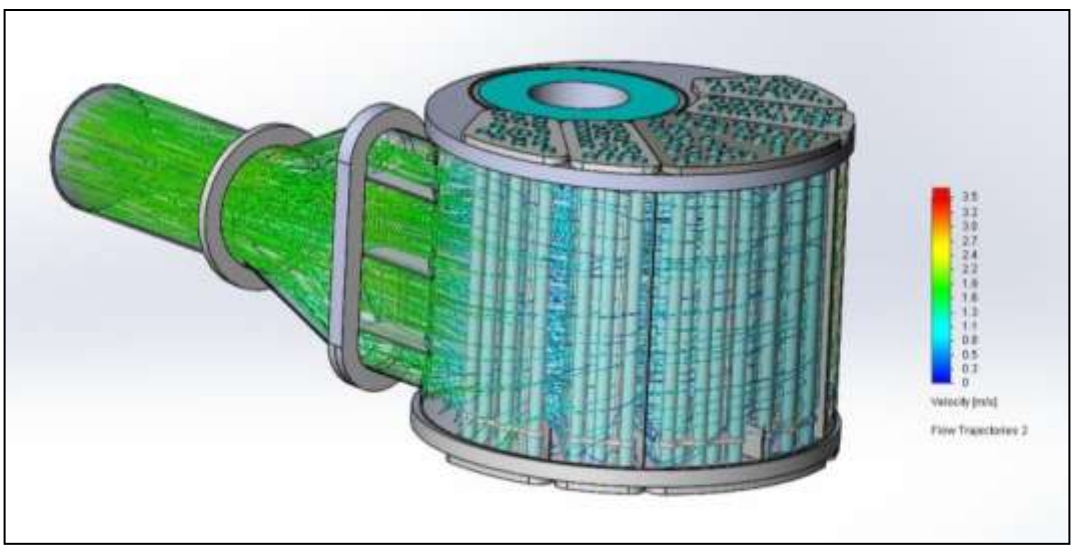

Figure 4 – Particle tracks colored by velocity through the Marinex 1250

2.2.1.2 UV Light Intensity Field

Trojan has developed in-house software capable of calculating UV light intensity distributions within a UV system. The software, referred to as Trojan's Lagrangian Dose Model (LDM), supports a number of intensity models and, for the purposes of this work, a cosine model using a series of Lambertian point source emitters was employed. The software includes reflection and refraction at air/quartz and quartz/water interfaces but does not include shadowing or reflection resulting from adjacent lamps and sleeves or reflection from UV unit walls. Table 2 and Table 3 below show the UV lamp and quartz sleeve characteristics of the Trojan Marinex product suite.

Table 2 – Lamp Characteristics

Nominal UV-C Output (Watts)	140
Arc Length (m)	1

Table 3 – Quartz Sleeve Characteristics

Outer Diameter	55 mm
Thickness	2.5 mm
Transmittance (%/mm)	90.8‡ (at 254 nm)
Index of Refraction	1.505526821 (254 nm)

‡Measured normal to surface and includes reflective losses. (Source: www.gequartz.com

Light Reflection, Absorption and Transmission

The intent of this section is to briefly explain the fundamental light theory of the reflection, transmission, and absorption of UV light in the material mediums. The theory explains how an emitted ray of light moves from a source through a media of a given refractive index n_1 (e.g. air) into a second media with refractive index n_2 (eg. quartz sleeve). Both reflection and refraction of the light ray may occur and what fraction of the light is reflected and what fraction is refracted (i.e. transmitted) can be described by the Fresnel equations (5 and 6 below).

Figure 5 below demonstrates the relationship between the reflection, transmission and absorption in the mediums. It can be seen when an incident light ray (I) strikes the interface between two medias of refractive indices n_1 (air) and n_2 (sleeve), part of the ray is reflected as ray (R_1) and part refracted as ray (T_1). The angles that the incident, reflected and refracted rays make to the normal of the interface are given as θ_i, θ_r and θ_t, respectively. Note, this relationship between the reflection, transmission and absorption is also applicable to the sleeve-water interface as well.

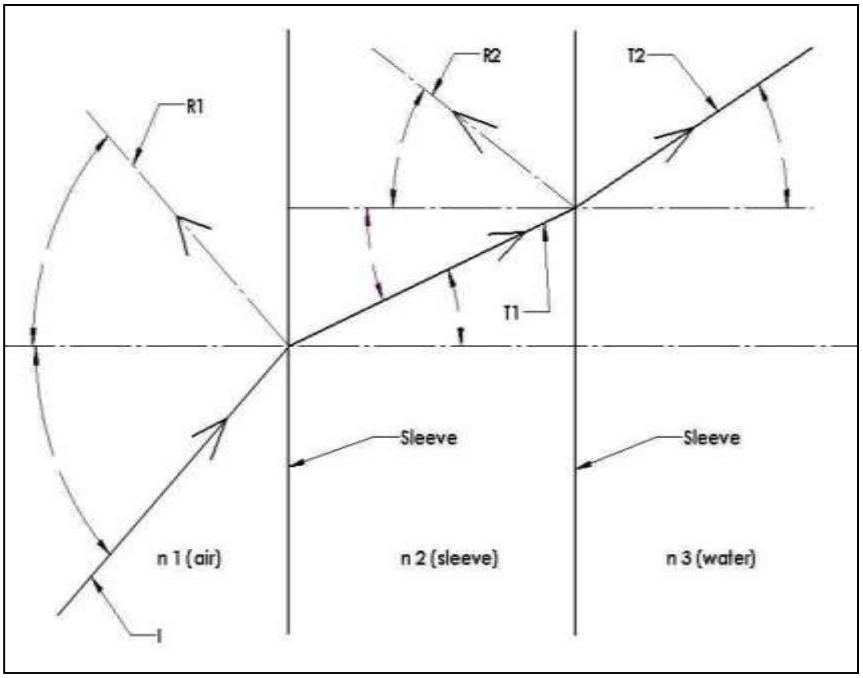

Figure 5 – Sketch of a light ray transmitted through different media (Air, Sleeve and Water)

The relationship between these angles is governed by the law of reflection:

$$\theta_{\mathrm{i}} = \theta_{\mathrm{r}} \qquad (3)$$

and Snell's law:

$$\frac{\sin\theta_{\mathrm{i}}}{\sin\theta_{\mathrm{t}}} = \frac{n_2}{n_1} \qquad (4)$$

The fraction of the incident UV light that is reflected from the interface is given by the reflectance *R* and the fraction that is refracted is given by the transmittance *T*. The calculations of *R* and *T* depend on polarization of the incident ray. Most sources of electromagnetic radiation contain a large number of atoms or molecules that emit light. The orientation of the electric fields produced by these emitters may not be correlated, in which case the light is said to be *unpolarized.* For the *s*-polarized light, the reflection coefficient is given by:

$$R_{\mathrm{s}} = \left|\frac{n_1\cos\theta_{\mathrm{i}} - n_2\cos\theta_{\mathrm{t}}}{n_1\cos\theta_{\mathrm{i}} + n_2\cos\theta_{\mathrm{t}}}\right|^2 = \left|\frac{n_1\cos\theta_{\mathrm{i}} - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}}{n_1\cos\theta_{\mathrm{i}} + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}}\right|^2 \qquad (5)$$

Where, the second form is derived from the first by eliminating θ_t using Snell's law and trigonometric identities. For the *p*-polarized light, the *R* is given by:

$$R_{\mathrm{p}} = \left|\frac{n_1\cos\theta_{\mathrm{t}} - n_2\cos\theta_{\mathrm{i}}}{n_1\cos\theta_{\mathrm{t}} + n_2\cos\theta_{\mathrm{i}}}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} - n_2\cos\theta_{\mathrm{i}}}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} + n_2\cos\theta_{\mathrm{i}}}\right|^2 \qquad (6)$$

Here P is termed p-like (parallel to the plane of incidence) and S is termed *s-like* (from *senkrecht*, German for perpendicular to the plane of incidence). If the incident light is un-polarized (containing an equal mix of *s*- and *p*-polarizations), the reflection coefficient is:

$$R = \frac{R_s + R_p}{2} \qquad (7)$$

The transmittance coefficient is:

$$T = 1 - R \qquad (8)$$

As with any form of electromagnetic radiation, UV intensity will also vary by the mechanism of absorbance. Beer's law states that the gradient in intensity is linearly relatedly to the intensity itself:

$$UVI(l) = UVI_0 e^{-\alpha l} \qquad (9)$$

where:

α	=	absorbance coefficient, 1/cm
UVI_0	=	intensity of incident radiation, mW/cm^2
l	=	path length in absorbing medium, cm

Applying the equations above, all the information about the UV light reflection, transmission and absorption in the material mediums can be calculated**.**

Figure 6 below, shows a comparison of the UV light intensity fields within the 500 and 1250 treatment units. The comparison is a two-dimensional representation of the centre-line cross-section through the systems.

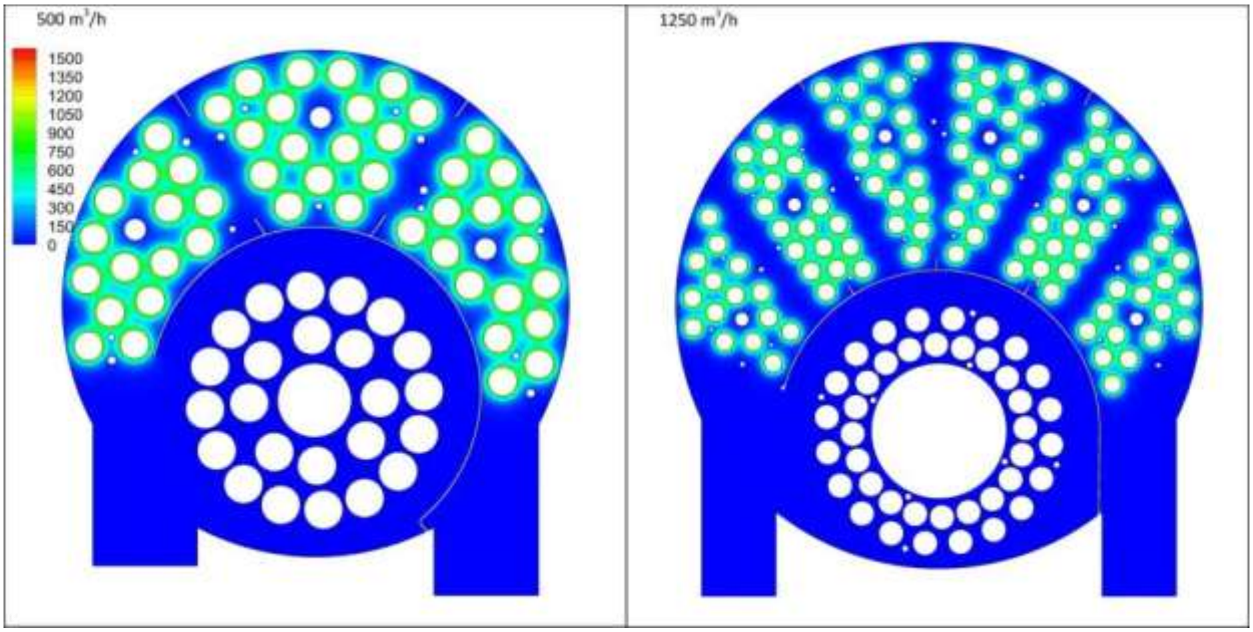

Figure 6 – Marinex 500 vs. 1250 showing center-line cross-section through systems displaying UV radiation intensity (W/cm^2).

2.2.1.3 Reduction Equivalent Dose (RED)

In addition to calculating the UV light intensity distribution within a UV unit, Trojan's LDM software is capable of importing the particle tracks created from the CFD simulations and integrating the dose delivered to each particle as it flows through the UV system. The resulting dose distribution is then converted into a Reduction Equivalent Dose (RED) using an appropriate dose-response for the organism of interest. This is performed by converting each particles dose to a log reduction (based on the specific microbe kinetics - see Equation 10 below), converting the log reduction to a survival ratio, summing all of the survival ratios, and dividing that sum by the number of particles in the distribution. That final value is the cumulative system survival ratio from which the systems log reduction can be determine and, using the known microbe kinetics, the RED can be calculated.

For this study, Reduction Equivalent Dose calculations were based on first order kinetics (Equation 10).

$$\frac{N}{N_0} = e^{-kD} \qquad (10)$$

where:
- N = number of viable micro-organisms after UV exposure
- N_0 = number of viable micro-organisms prior to UV exposure
- k = inactivation rate constant (cm²/mJ)
- D = UV dose applied during disinfection (mJ/cm²)

Each micro-organism has a different rate constant (k); the constant used for this study is 0.0460517 cm^2/mJ which corresponds to a D_{10} (dose per log reduction) of 50 mJ/cm^2. This value was selected based on the dose response behavior observed in collimated beam studies performed with *Tetraselmis*.

2.2.2 Calculated Reduction Equivalent Dose (RED)

Tables 4 and 5 below show the calculated RED values for the Marinex product suite during ballast and deballast cycles. It can be seen that the UV Dose of all of the models is within +/-10% of the tested 500 m^3/h system.

Table 4 – Calculated UV Doses of Ballast Cycle for Trojan Marinex product suite

Model	TRC (m^3/h)	Number of UV Lamps	Ballast Cycle RED (mJ/cm^2)	Variance from Model 500
150	150	14	49.9	-9%
250	250	24	53.8	-1%
500	500	48	54.6	0%
750	750	62	54.4	0%
1000	1000	84	54.6	0%
1250	1250	110	57.6	5%
1500	1500	124	52.2	-4%

Table 5 – Calculated UV Doses of DeBallast Cycle for Trojan Marinex product suite

Model	TRC (m^3/h)	Number of UV Lamps	Deballast Cycle RED (mJ/cm^2)	Variance from Model 500
150	150	14	49.6	-7%
250	250	24	55.1	3%
500	500	48	53.4	0%
750	750	62	53.4	0%
1000	1000	84	53.9	1%
1250	1250	110	55.7	4%
1500	1500	124	53.2	0%

2.2.3 Dose Distribution Curves

The Dose Distribution curves are summarized in the figures below for the system operating in both Ballast model and Deballast mode.

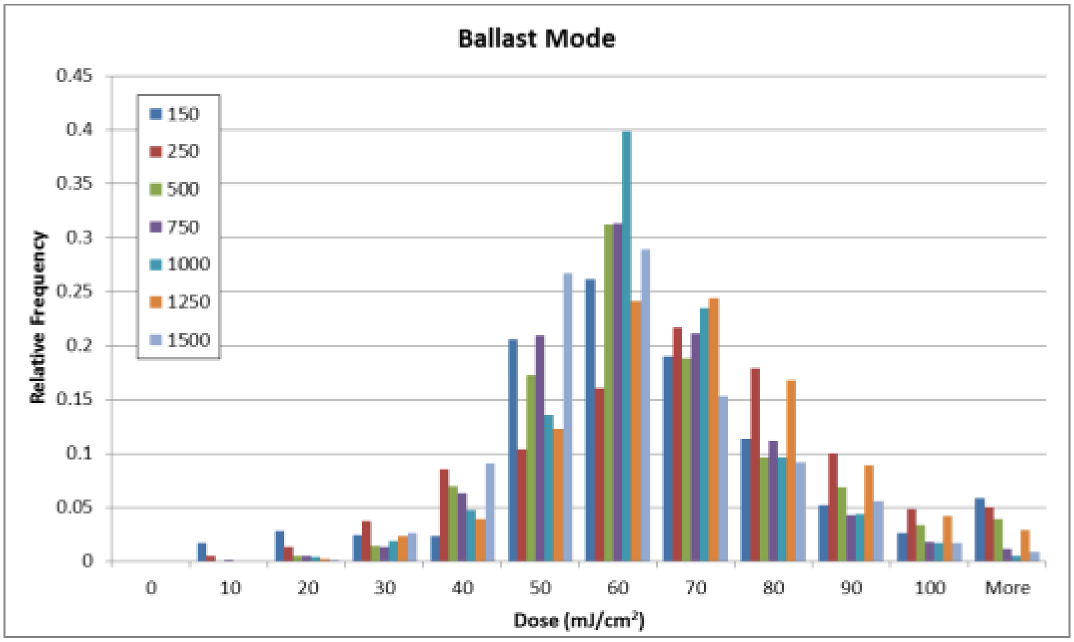

Figure 7 – Dose Distribution Summary for Marinex Product Suite on Ballast Cycle

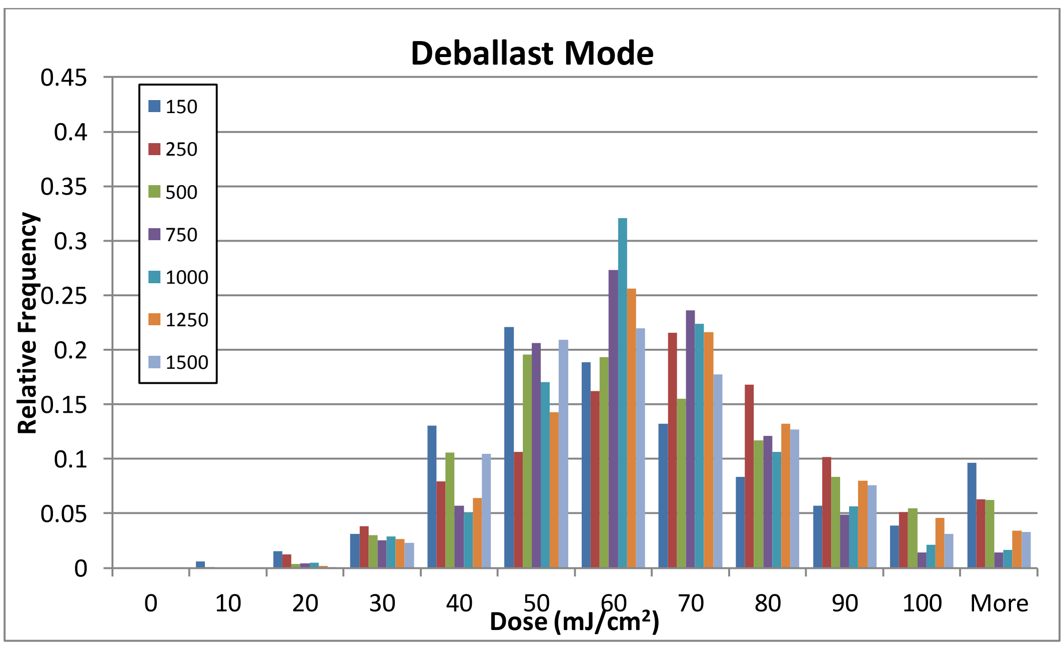

Figure 8 – Dose Distribution Summary for Marinex Product Suite on Deballast Cycle

2.2.4 Consideration of Upstream and Downstream Pipe Geometry

Upstream Pipe Geometry

The Trojan Marinex system is unique, in that the filter elements and the UV lamps are housed within a single treatment vessel (no piping in-between the filter and the UV). On the ballast cycle (uptake), the water passes through the filter elements prior to entering the UV portion of the treatment unit. The filter elements provide a significant flow restriction and thereby condition the flow as it enters the UV portion of the system, and as such, it is not impacted by the piping geometry upstream of the system.

On the deballast cycle (discharge), however, the water flows directly into the UV portion of the treatment unit and therefore performance could be influenced by upstream piping geometry. To look at the potential for impacts of upstream piping geometry on the performance of the system during deballast mode, we have modeled one model, the 500 m^3/h system, with several different piping configurations and compared the resultant RED for each. In some cases the system may be installed with a course screen mounted directly to the inlet flange to protect the UV lamps from any large debris should such protection not already exists within the ballast water piping to protect pumps etc. The presence/absence of this course screen has been included in the modeling scenarios.

A summary of the modeling results and schematics of the piping scenarios are provided below. The upstream piping and the presence/absence of the screen has negligible impact on the system performance, therefore we have modelled the system comparisons using only one piping setup; straight pipe with no screen.

Table 6 – Calculated RED Delivered by Model 500 Under Different Upstream Piping Configurations

Configuration	RED [mJ/cm^2]	
	With Screen	Without Screen
Straight Pipe	53.39	53.29
Up Elbow	54.56	54.16
Down Elbow	54.66	54.22
Sideways Elbow	53.34	53.73

Down Elbow

Sideways Elbow

Up Elbow

Figure 8 – Upstream Piping Conditions Modelled

<u>Downstream Pipe Geometry</u>

Trojan typically specifies a minimum distance downstream of its closed vessel UV systems of one pipe diameter before any piping bends, valves or transitions are installed. For the Marinex product suite, the minimum distance from the UV portion of any system to its outlet is already two pipe diameters. In addition, all of the systems have converging, nozzle-type transitions downstream of the UV section that has not only flow stabilizing characteristics but also an acceleration effect. These combined factors make the downstream piping insignificant to the UV system performance and for that reason only a simple, straight pipe downstream of the treatment unit was utilized for all of the CFD simulations.